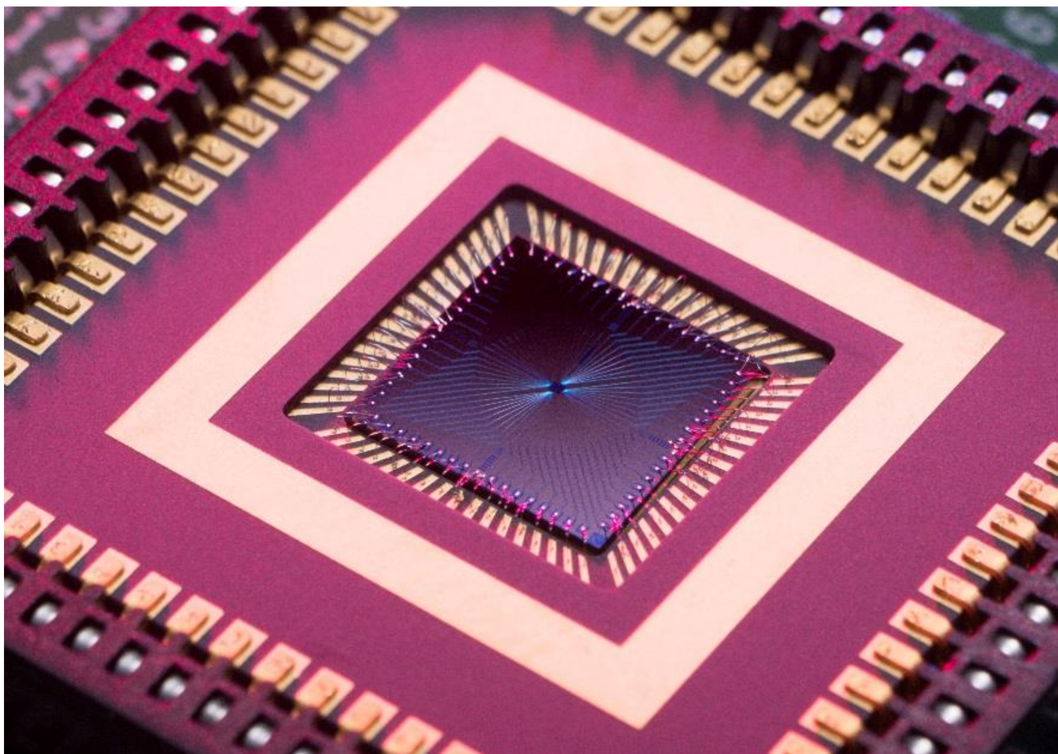
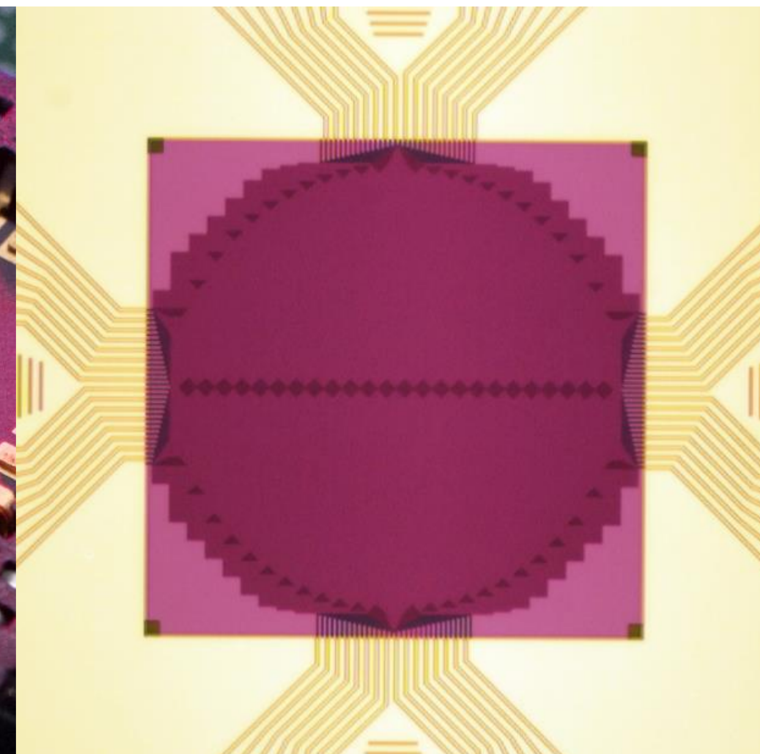
Superconducting Nanowire Single Photon Detectors for Deep Space Optical Communication

Single Photon Workshop, Boulder

Matt Shaw, Jason Allmaras, Andrew Beyer, Ryan Briggs, Angel Velasco, Francesco Marsili and William Farr

Jet Propulsion Laboratory, California Institute of Technology

JPL SNSPD Development Team

JPL Staff


Matt Shaw


Andrew Beyer


Ryan Briggs


Marc Runyan


Angel Velasco

Huy Nguyen

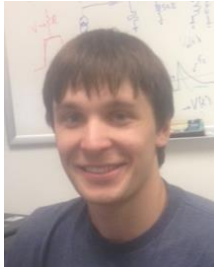
Postdocs


Emma Wollman


Boris Korzh

Jeff Stern
1961-2013

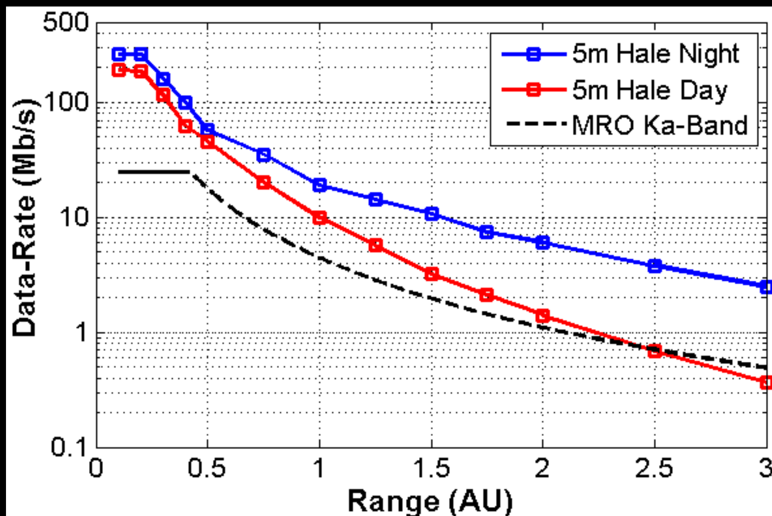
Graduate Students and Visitors


Jason Allmaras

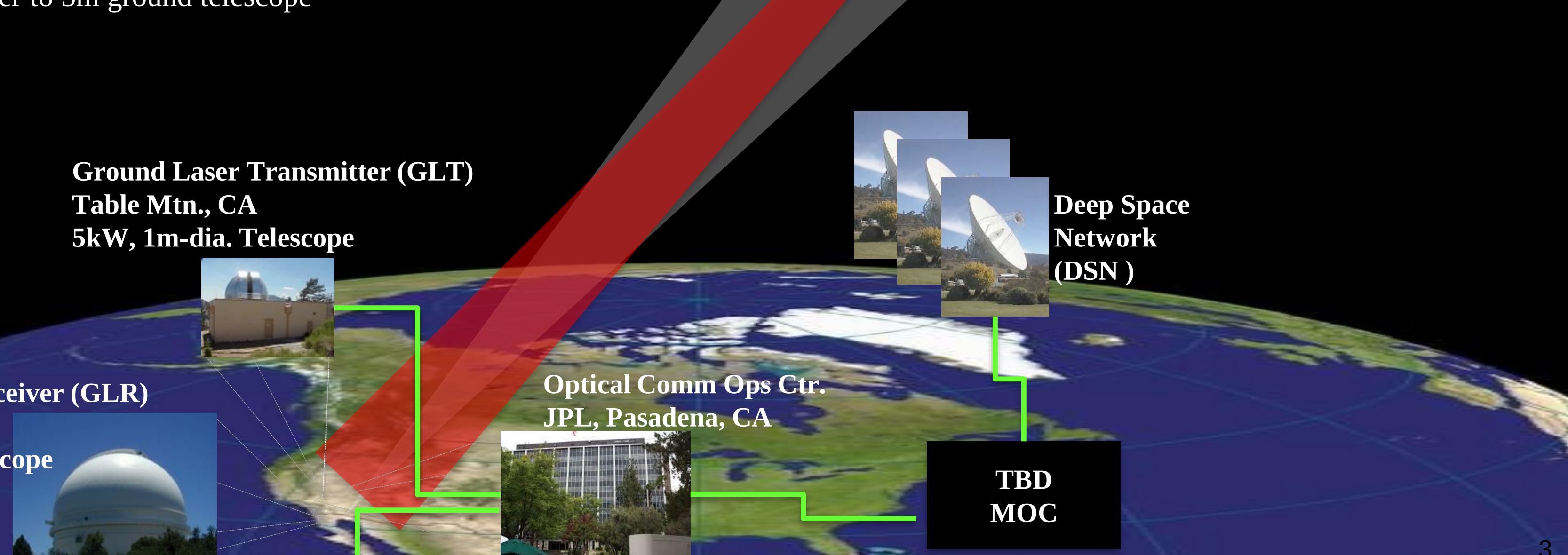

Eric Bersin


Simone Frasca

DSOC Tech Demo Mission

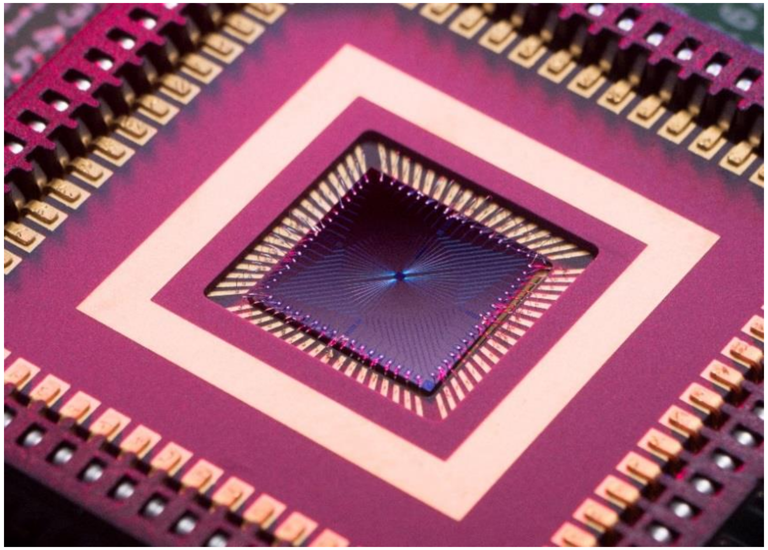


Performance using 4W average laser power w/22 cm flight transceiver to 5m ground telescope

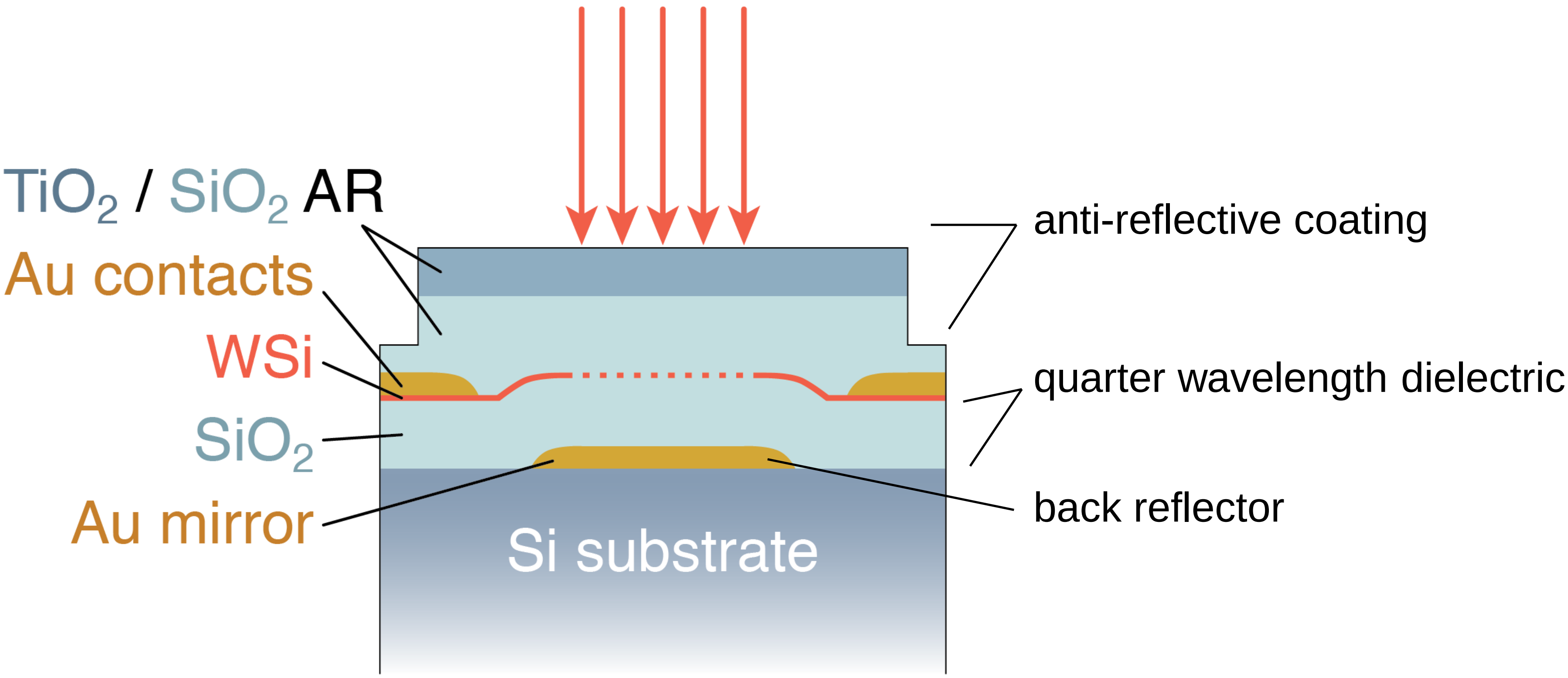


DSOC Project Overview

- Phase A of NASA Technology Demonstration Mission
- Ground system funded by NASA SCaN
- Flight terminal planned to launch on PSYCHE spacecraft in 2023
- Projected downlink data rates from 200 kbps - 265 Mbps
- Developing a 320-µm 64-pixel WSi SNSPD array for the ground receiver



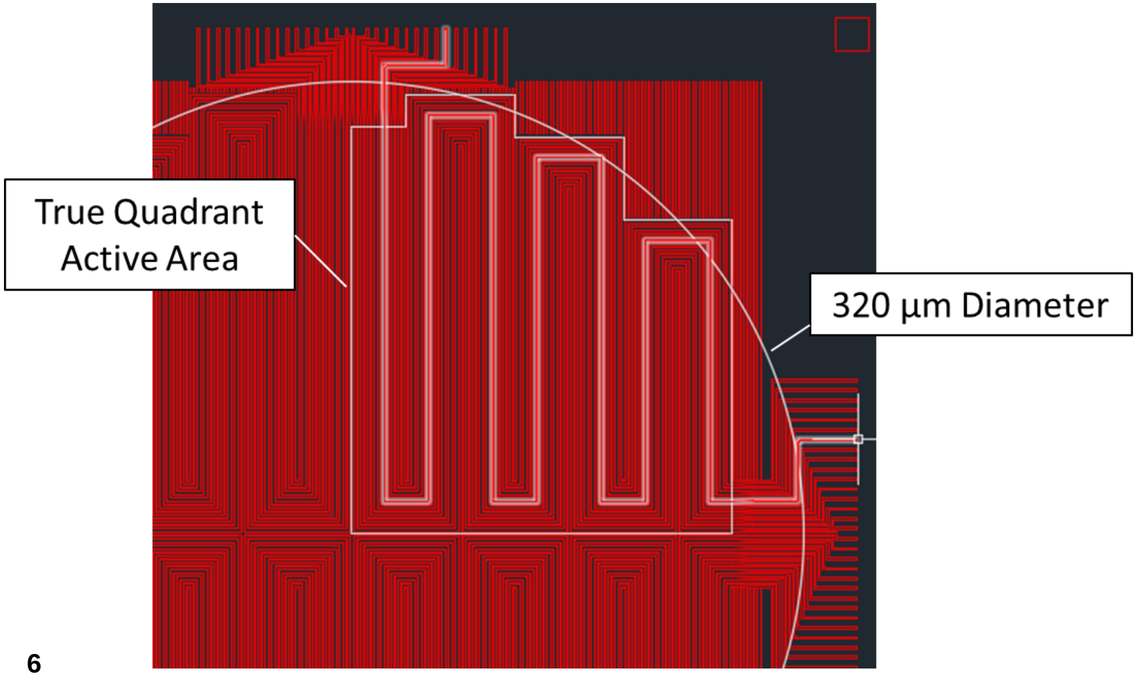
WSi SNSPD Architecture

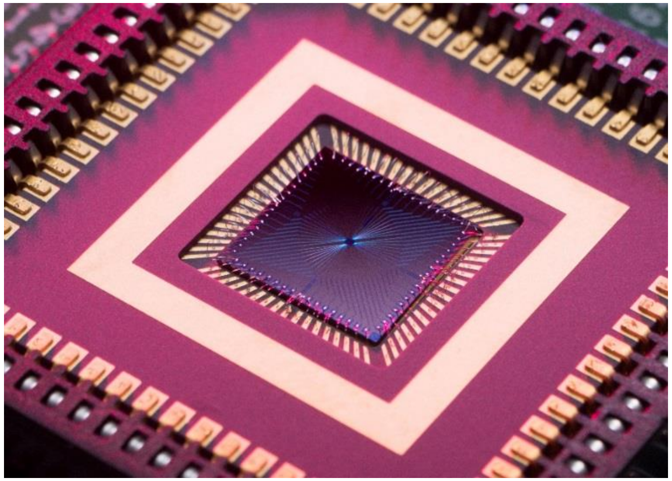


- Photosensitive nanowire element is embedded in a vertical quarter-wave cavity

64-Pixel SNSPD Array

- 64-pixel WSi SNSPD array embedded in optical cavity optimized for 1550 nm
- 320-µm dia. free-space coupled active area, 4 quadrants, 16 co-wound wires per quadrant
- 13.3% nanowire fill factor: 4.5 x 160 nm wires on a 1.2 µm pitch
- Two-layer AR coating to enhance efficiency at low fill factor: 74% system detection efficiency
- 62 out of 64 measured nanowires plateau
- Full 64-channel readout system and 64-channel time-to-digital converter





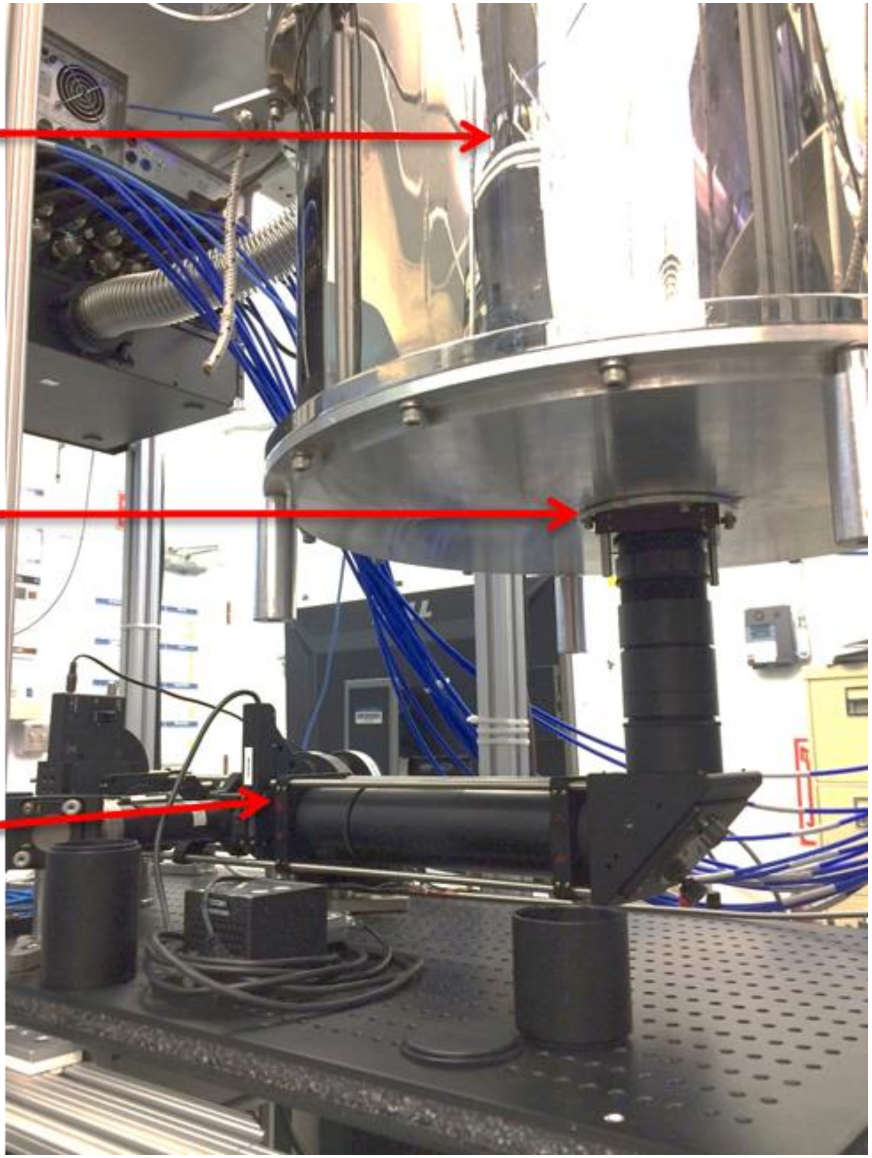
Free Space Coupling

- Efficient coupling to large apertures requires free space coupling
- Previous demos have all used fiber
- 300 K vacuum window
- 40 K, 4 K IR filters to block thermal background
- Engineering tradeoff between efficiency and false counts
- Must consider finite numerical aperture of detector

Cryostat

Cryostat window

Free space optical system



Project Goals and SNSPD Performance

	DSOC Goals	Progress to date	Capability Acheived
Detection Efficiency	>50% minimum >70% desired	93% (fiber-coupled single pixel) 74% (Free Space, 320 µm array)	✓
Timing Jitter	100 ps (1-sigma)	50 - 70 ps (1-sigma) (not including TDC)	✓
False Counts	< 10 kcps / pixel free space coupled	< 7 kcps / pixel (320 µm array)	✓
Maximum Count Rate	830 Mcps (264 Mbps, 0.2 AU, night cruise)	1.26 Gcps (20 Mcps / pixel, 63 pixels)	✓
Active Area	260 µm diameter (35 µrad seeing, Palomar daytime)	320 µm diameter (50 µrad seeing, Palomar daytime)	✓
Numerical Aperture	f/1.2	f/4	

1550 nm operating wavelength

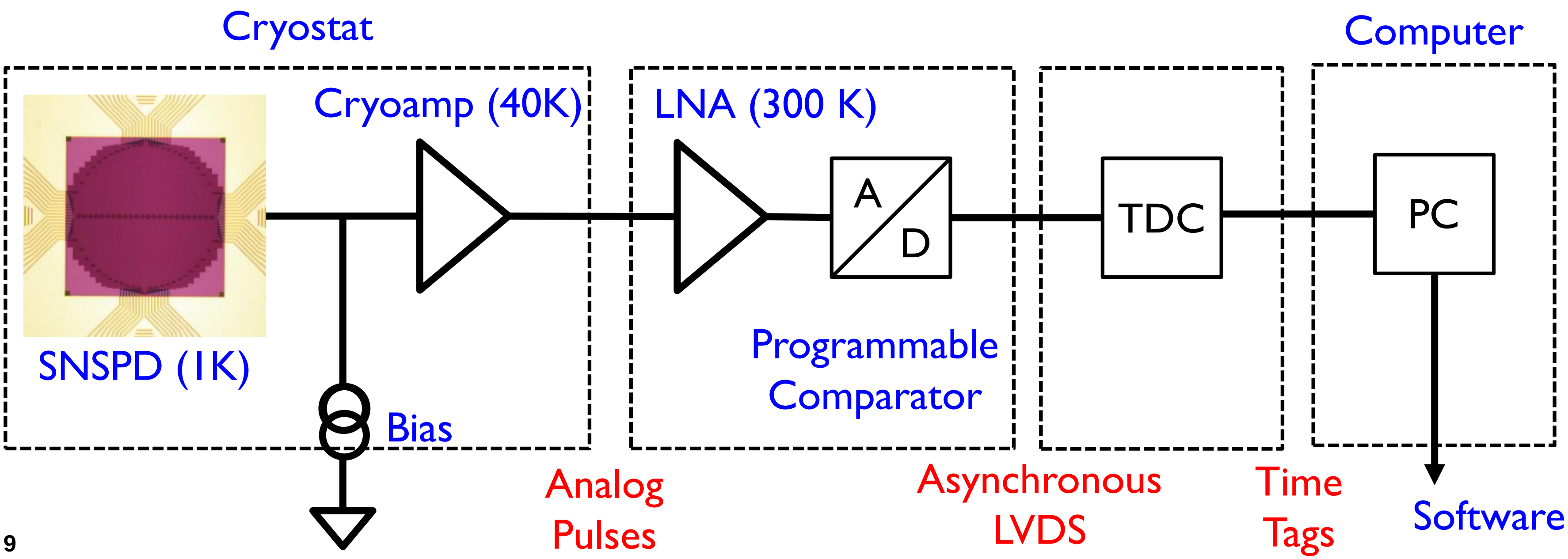
Free space coupled

1 K operating temperature

SNSPD Array Readout Concept

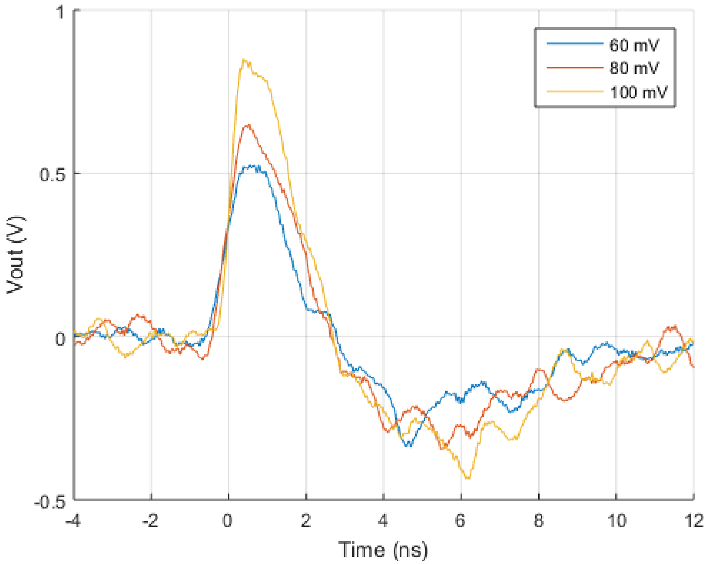
- Direct readout of 64 channels into an FPGA
- Brass flex circuits from < 1 – 40 K
- DC-coupled cryogenic amplifiers
- Copper flex circuits from 40 - 300 K
- Room temperature amplifiers and comparators
- FPGA-based time tagger
- Currently setting up SNSPD optical communication testbed

16-channel brass RF flex circuit

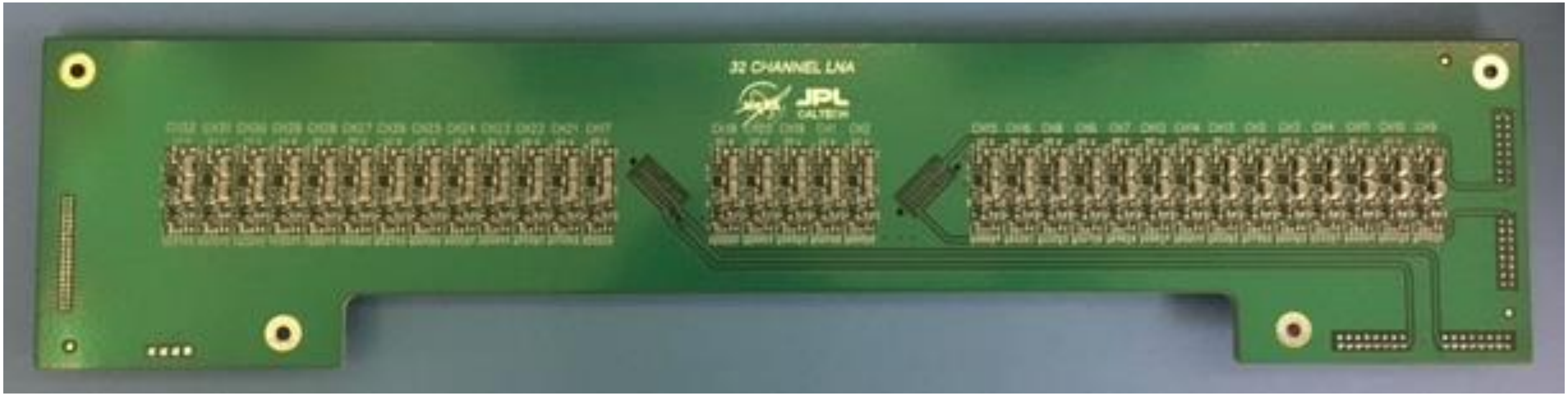


DC Coupled Cryogenic Amplifiers

- 2x 32-channel amplifier boards operated at 40 K
- 32 dB total gain
- Low-cost commercial cell phone components
- RFMD SGL-0622z cryogenic RF amplifier
- Broadcom ATF-35143 Psuedomorphic HEMT
- DC coupled with 50 ohm terminated input
- Detector bias added on amplifier board



SNSPD output pulses at different bias points



32-channel cryogenic amplifier board, operated at 40 K

Time to Digital Converter Development

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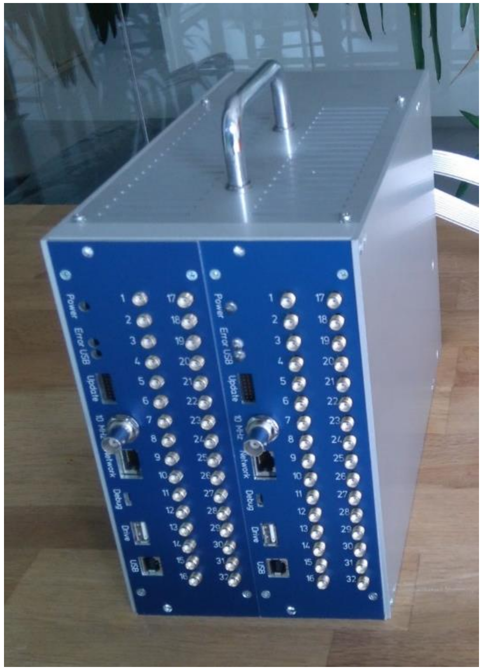
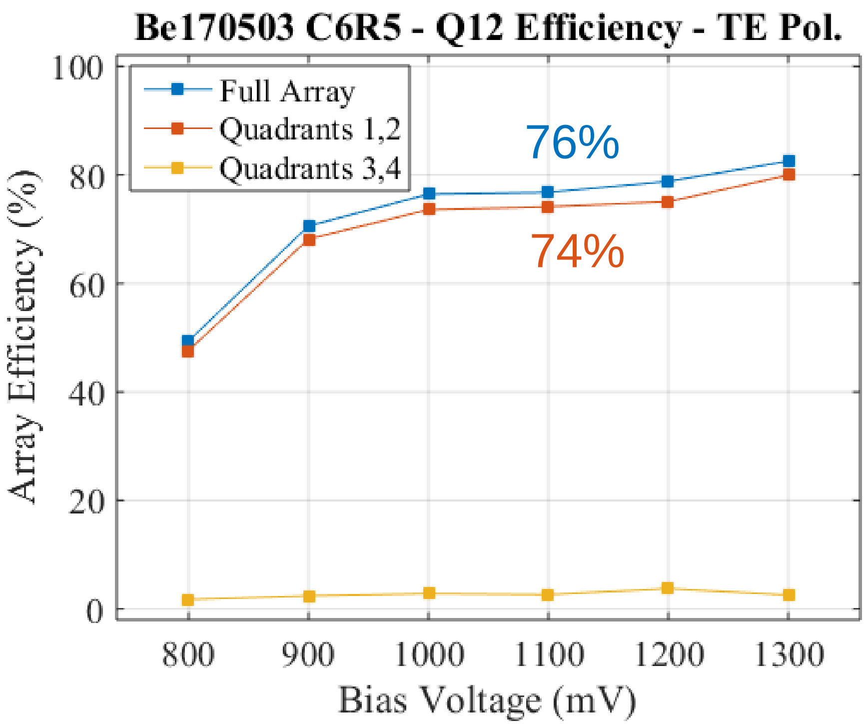
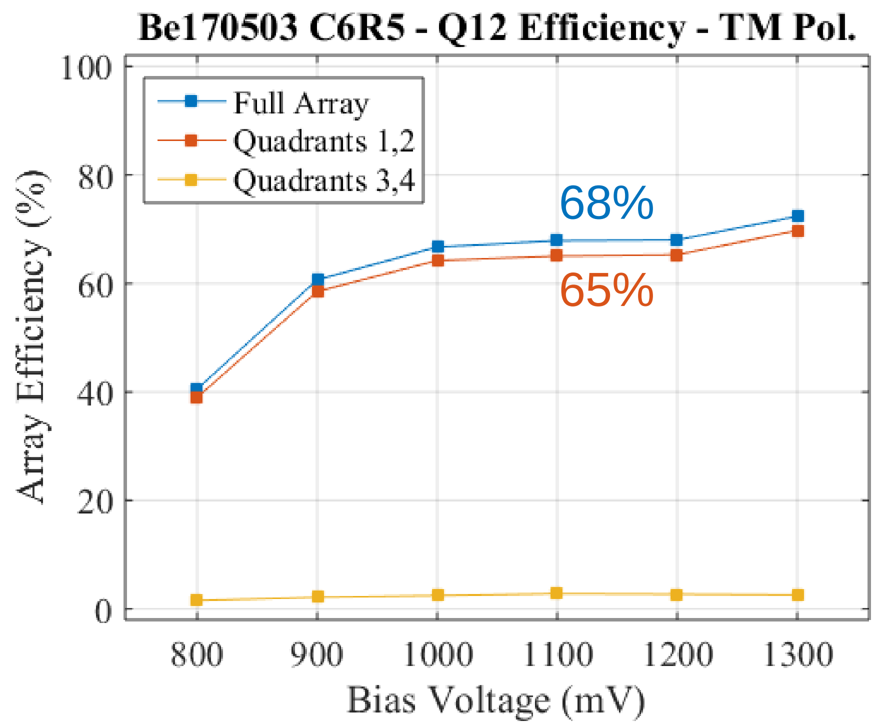
- Asynchronous time tagging receiver approach
- Need to tag photon arrivals across 64 channels with ~150 ps resolution
- Need to stream data into receiver FPGA at ~ gigatag / second count rates
- Prototype TDC can fill 512 Mtag buffer at rates up to 600 Mtps w/ 166ps resolution
- Streaming TDCs are currently under development

Prototype 64-channel TDC (Voxtel)


2x 32-channel comparator modules (UQD)

Efficiency Measurements

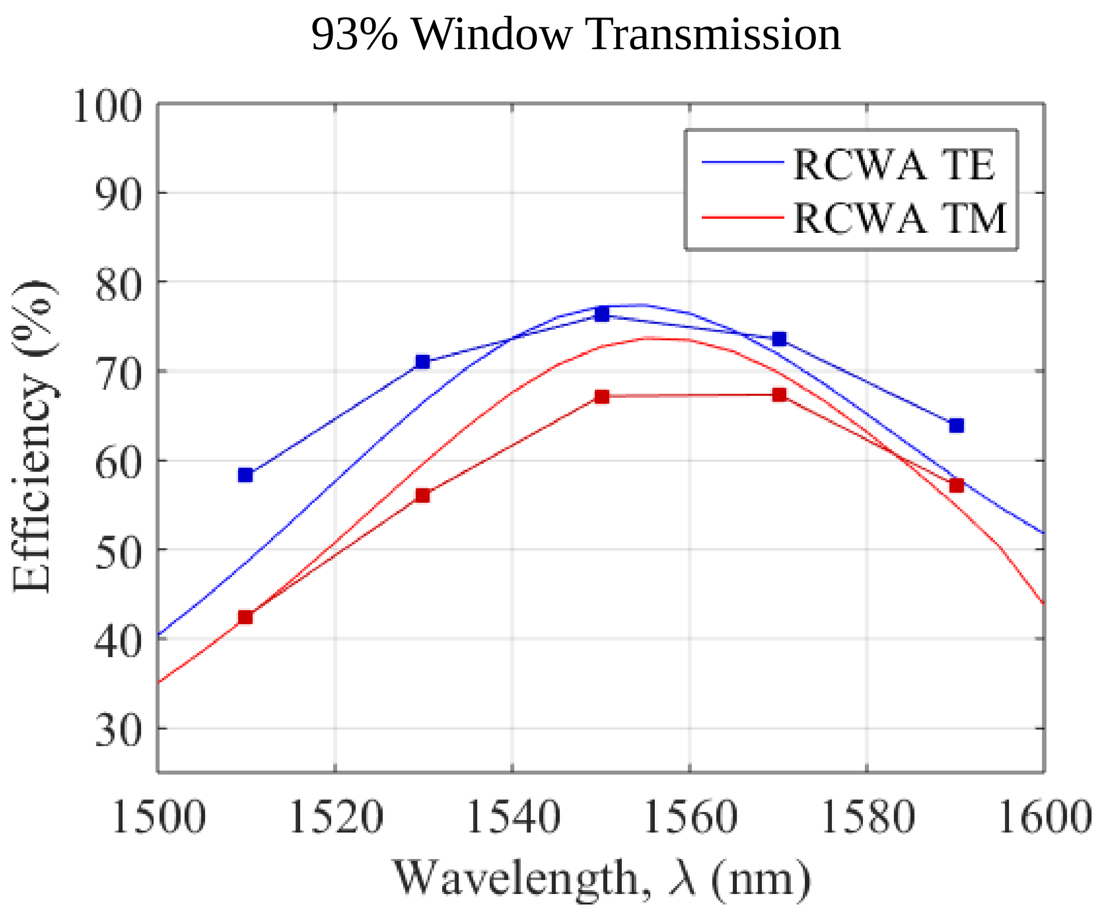




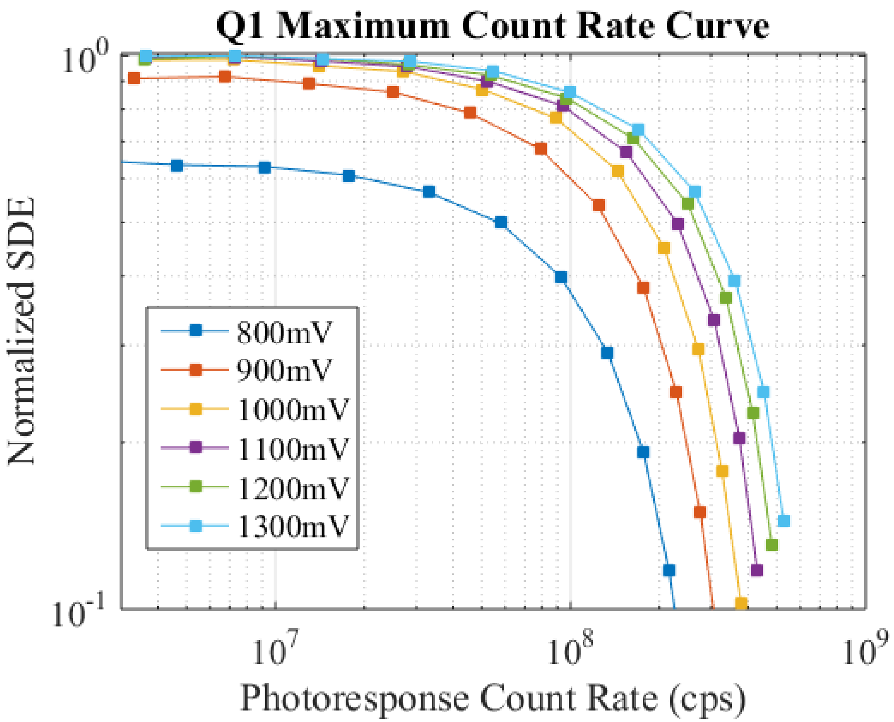
- System detection efficiency measured through cryostat window, 40K and 4K IR filters
- Measured SDE by focusing 50 um spot into one half plane (32 channels)
- Measured 74% efficiency in TE polarization at 1550 nm, 65% in TM

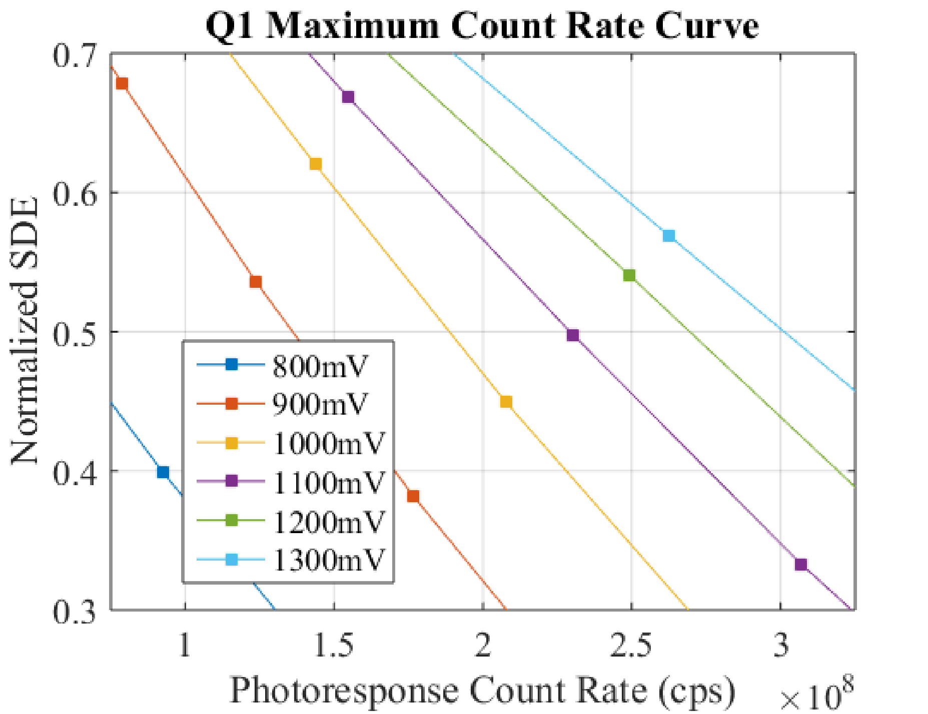
Efficiency Measurements

- Cavity is well centered
- Efficiency matches RCWA simulation assuming 93% total transmission (97.6% per window)



Maximum Count Rate





- 3dB MCR of 15 Mcps at the back of the plateau, 22 Mcps at the front
- DC coupled cryogenic amplifier chain (commercial components)
- For 63 working pixels, this gives an array MCR of 900 Mcps at the back, 1.3 Gcps at the front

Device Timing Jitter

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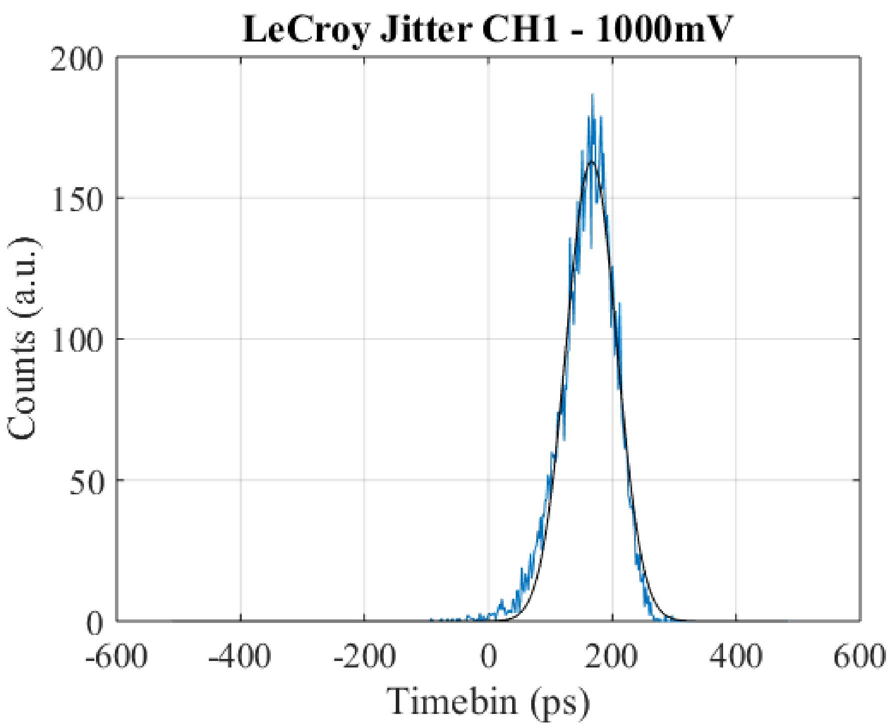
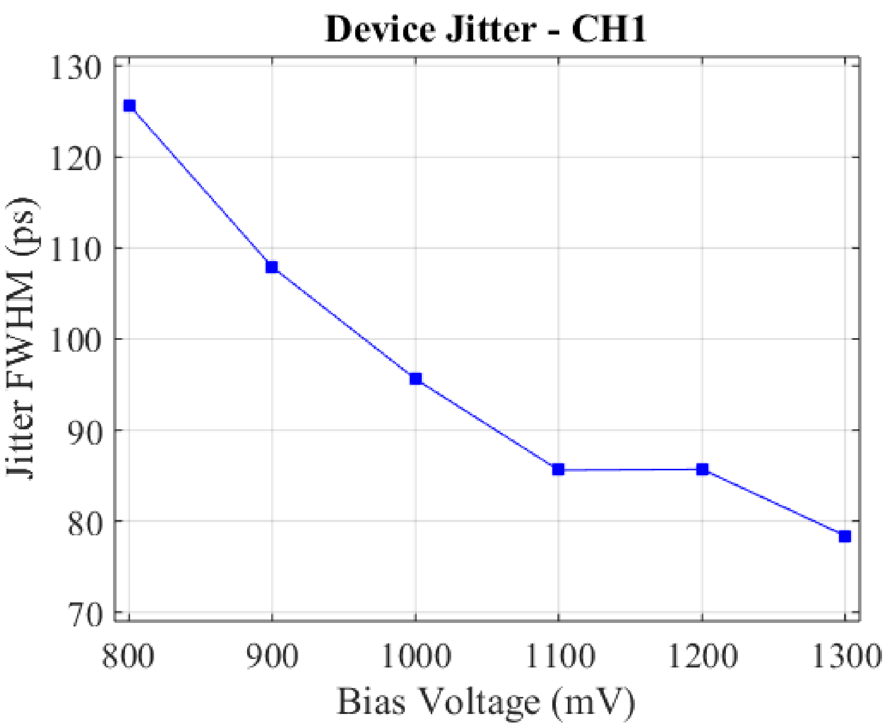
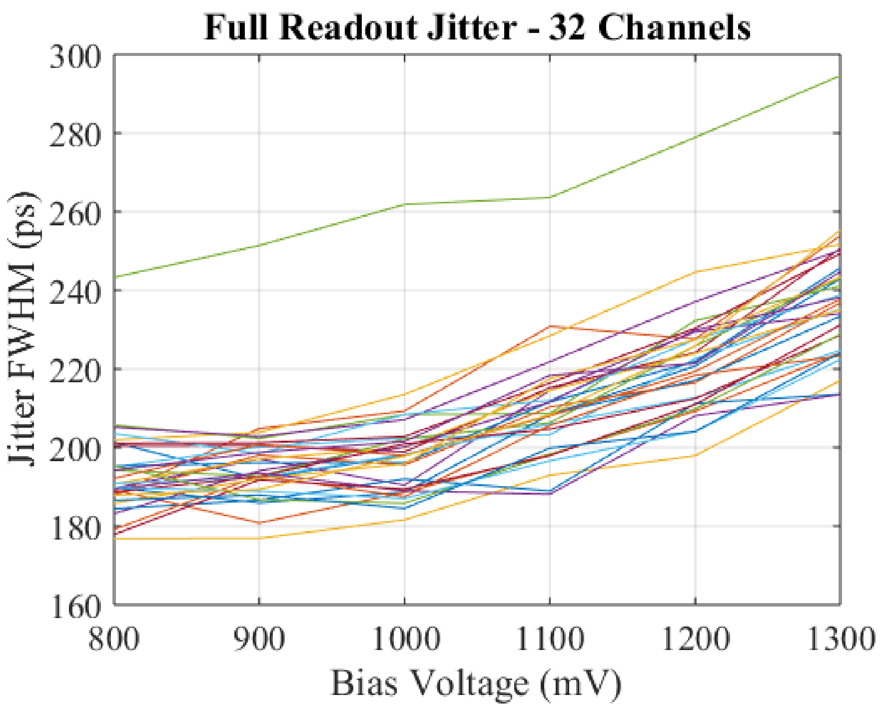
- Single pixel timing jitter measured using mode-locked laser and oscilloscope
- IRF is close to Gaussian
- 125 – 79 ps FWHM (54 – 34 ps 1-sigma)

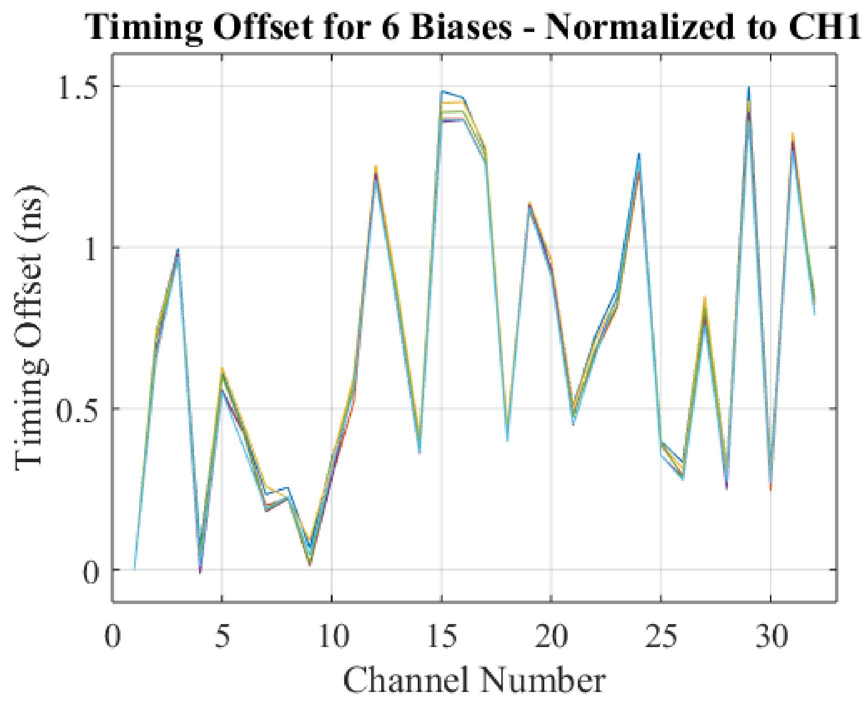




System Timing Jitter

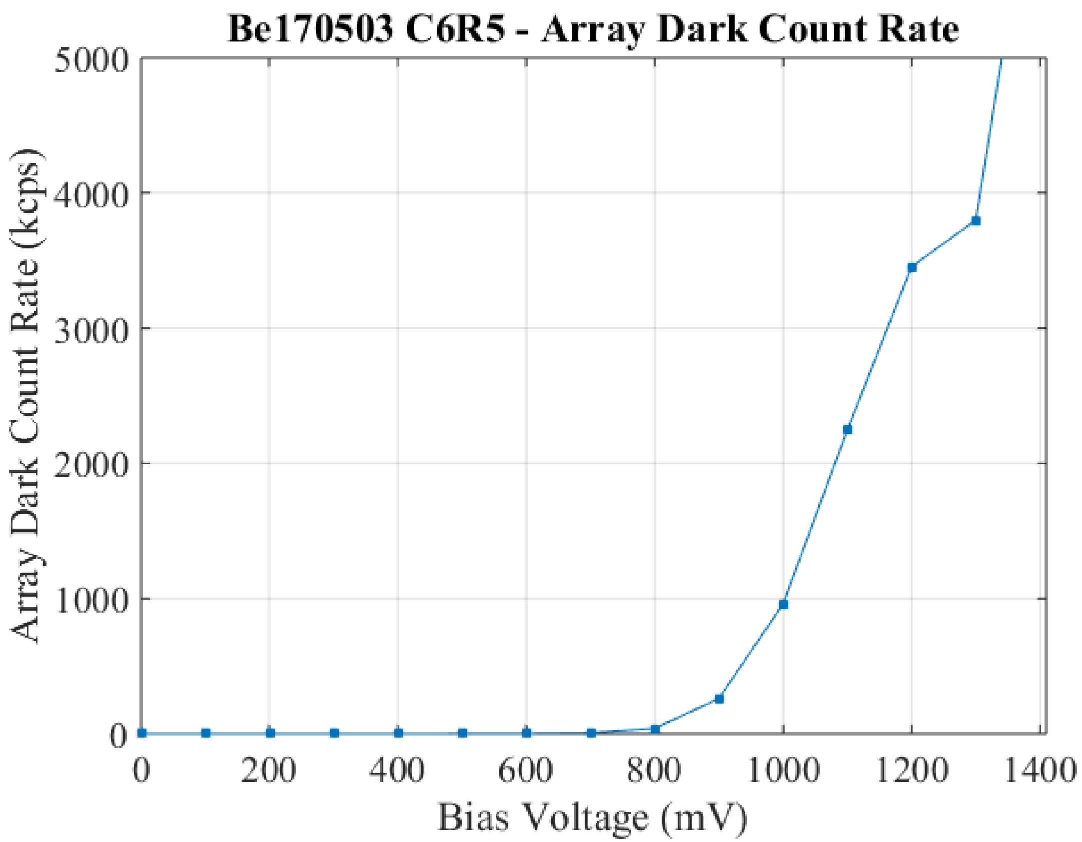
- Full system timing jitter is below 250 ps FWHM (109 ps 1-sigma) at all operating points
- Also extracted timing offset between channels from same data
- Timing offsets very similar to last array, so dominated by length matching in the readout



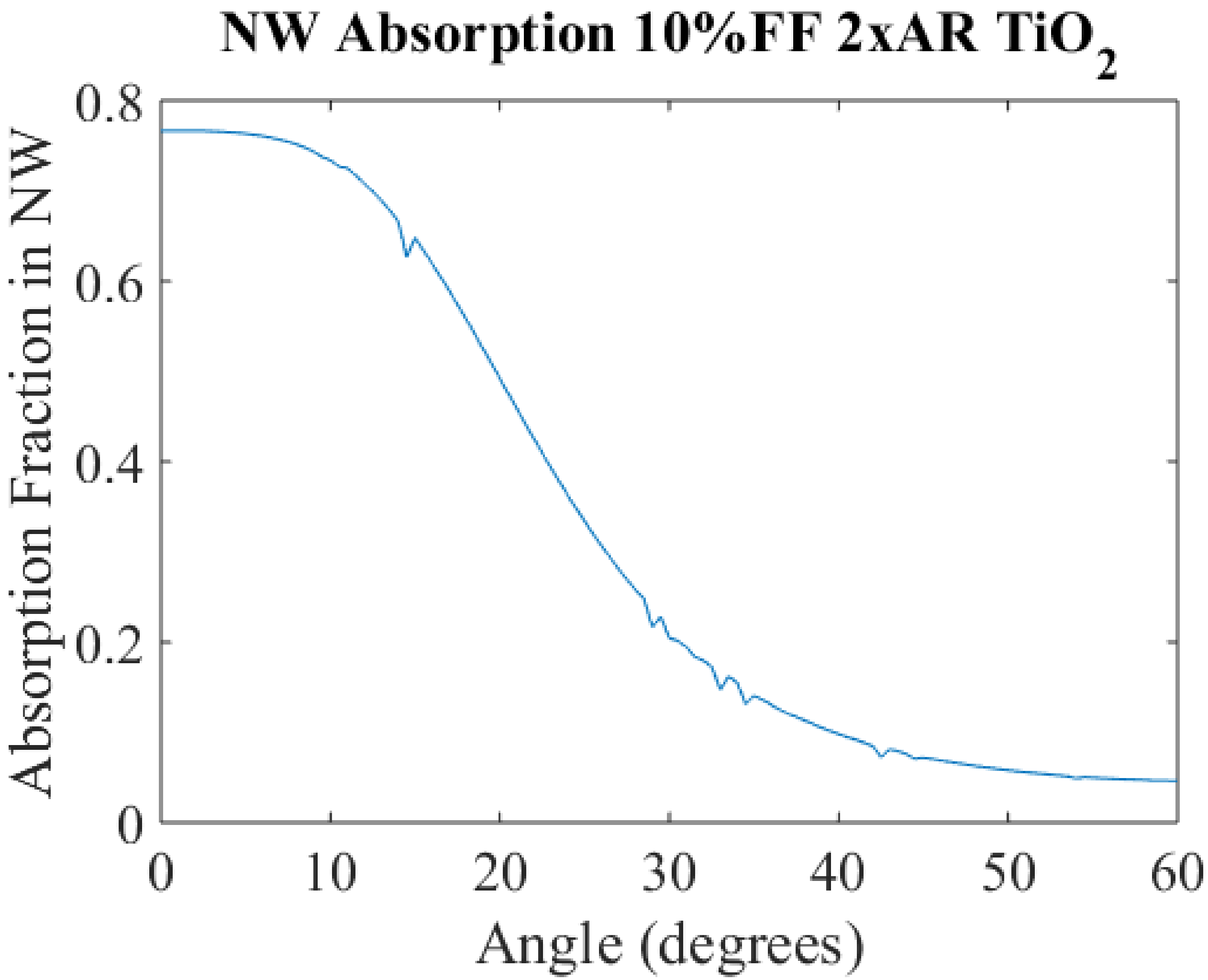


False Count Rate

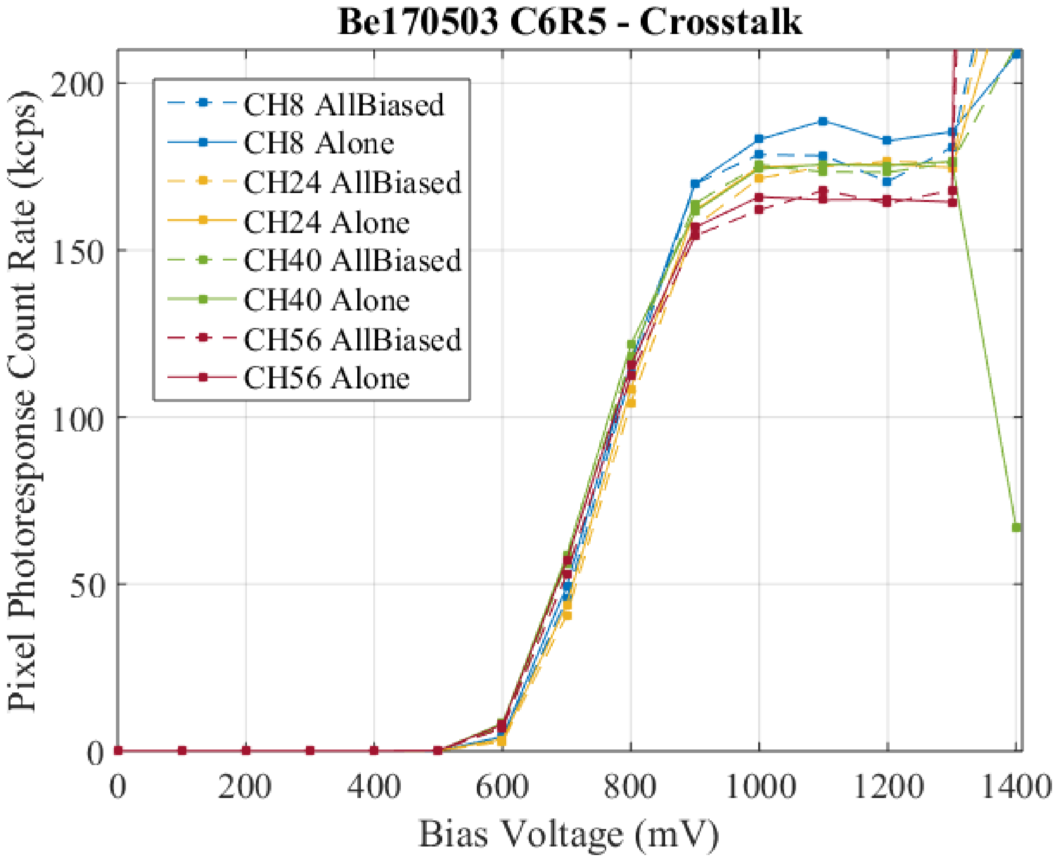
- 350 kcps at back of plateau – 3.8 Mcps at front of plateau
- Can implement cryogenic spatial filter or a shortpass to improve this



Angular Acceptance of Detector

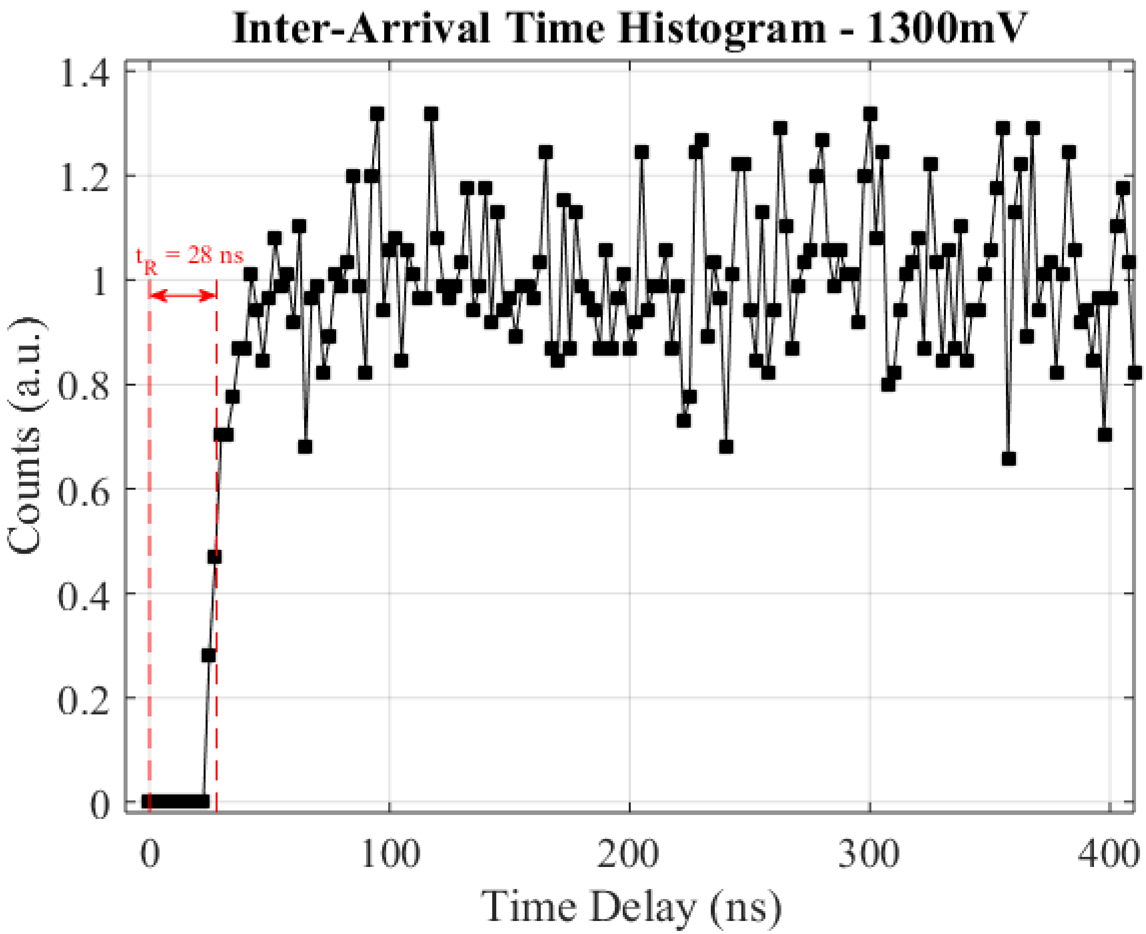


Absence of Crosstalk



- No crosstalk is observed with 1200 nm pitch co-wound arrays
- Severe crosstalk was observed with 320-800 nm pitch co-wound arrays
- From scaling, crosstalk is believed to be thermal
- Physics of crosstalk is under study with a generalized electrothermal model

Absence of Afterpulsing



- Interarrival time histogram shows no presence of afterpulsing

Summary

- The aggressive goals of the DSOC project have stimulated rapid advancement in SNSPD detectors for ground terminals
- 64-pixel WSi SNSPD arrays now have sufficient active area to couple efficiently to a 5-meter telescope and perform time-correlated single photon counting at gigacount per second count rates